Prospects of Very Long Base-Line Neutrino Oscillation Experiments with the JAERI-KEK High Intensity Proton Accelerator

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In this paper, we discuss physics potential of the Very Long Base-Line (VLBL) Neutrino-Oscillation Experiments with the High Intensity Proton Accelerator (HIPA), which is planned to be built by 2006 in Tokaimura, Japan. We propose to use conventional narrow-band ν_μ beams (NBB) from HIPA for observing the $\nu_\mu \to \nu_e$ transition probability and the ν_μ survival probability. The pulsed NBB allows us to obtain useful information through counting experiments at a huge water-Cherenkov detector which may be placed in our neighbor countries. We study sensitivity of such an experiment to the neutrino mass hierarchy, the mass-squared differences, the mixing angles and the CP phase of the 3×3 lepton flavor mixing matrix (MNS matrix). The CP phase can be measured with a 100kt detector if both the mass-squared difference and U_{e3} elements of the MNS matrix are sufficiently large.

1 Introduction

Very long base-line (VLBL) neutrino-oscillation experiments is one of the attractive experiments in the near future. In this paper, we discuss physics potential of the VLBL neutrino-oscillation experiments with the High Intensity Proton Accelerator (HIPA), which was approved by the Japanese government last December and will be built by 2006 in Tokaimura, Japan[a].

The JHF Neutrino Working Group proposes the first phase neutrino-oscillation experiments with HIPA and Super-Kamiokande, whose base-line length is 295 km. The Letter of Intent (LOI) is available on their web site[1]. In this paper, we discuss possible future VLBL neutrino-oscillation experiment between HIPA and Beijing. The base-line length of this experiment is about 2100km.

In our analysis, we propose to use the conventional pulsed narrow-band ν_μ beams (NBB) from HIPA for observing the $\nu_\mu \to \nu_e$ transition probability and the ν_μ survival probability at a huge 100kt-level detector in Beijing. We can then obtain useful information through counting experiments *e.g.* by adopting a water-Cherenkov detector. We study the sensitivity of such experiment to the neutrino mass hierarchy, that is the sign of mass-squared differences, the mixing angles and the CP phase in the 3×3 lepton flavor mixing matrix, the MNS (Maki-Nakagawa-Sakata) matrix [2], and the magnitudes of the two mass-squared differences. We can determine the neutrino mass hierarchy pattern from this experiment. The CP phase can be measured if both the mass-squared difference responsible for the solar neutrino oscillation and all three mixing angles are sufficiently large.

[a]More information is on http://jkj.tokai.jaeri.go.jp/.

2 MNS matrix

In this analysis, we assume three neutrino spices[b]. We define the MNS matrix as

$$\begin{aligned} J^\mu_{cc} &= (\overline{d}, \overline{s}, \overline{b})\gamma^\mu(1-\gamma_5)V^\dagger_{\text{CKM}}(u,c,t)^T \\ &+ (\overline{e}, \overline{\mu}, \overline{\tau})\gamma^\mu(1-\gamma_5)V_{\text{MNS}}(\nu_1,\nu_2,\nu_3)^T \,, \end{aligned} \tag{1}$$

where u, d, c, s, t, b are the quark mass-eigenstates, e, μ, τ are the charged-lepton mass-eigenstates, and ν_i $(i = 1, 2, 3)$ is the neutrino mass-eigenstate. The MNS matrix connects the mass eigenstate ν_i $(i = 1, 2, 3)$ to the flavor eigenstate ν_α $(\alpha = e, \mu, \tau)$

$$\nu_\alpha = \sum_{i=1}^{3} (V_{\text{MNS}})_{\alpha i} \;\; \nu_i \,. \tag{2}$$

V_{MNS} can be parameterized as

$$V_{\text{MNS}} = U_{\text{MNS}}\mathcal{P} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\varphi_2} & 0 \\ 0 & 0 & e^{i\varphi_3} \end{pmatrix} , \tag{3}$$

[b]If the LSND [3] results are confirmed, we have to revise this analysis.

where the matrix $\mathcal{P}$ is the Majorana-phase matrix. If neutrinos were not Majorana particles, this phase matrix can be absorbed away by the phases of the right-handed neutrino fields. The neutrino oscillation experiments are not sensitive to this phase matrix. The matrix $U_{\rm MNS}$ has three mixing angles and one CP phase, just like the CKM matrix. We can always take these upper-right elements, U_{e2}, U_{e3}, and $U_{\mu 3}$, as the independent parameters of the MNS matrix. Both U_{e2} and U_{e3} have the non-negative real values and U_{e3} can be complex number, which are related to the three mixing angles and one CP phase. The other elements are determined by the unitarity conditions [4].

We take into account existing constraints for the MNS matrix and the mass-squared differences as follows. From the atmospheric-neutrino oscillation measurements [5,6],

$$\sin^2 2\theta_{\rm ATM} = 1.0\,, \delta m^2_{\rm ATM} = 3.5\times 10^{-3} ({\rm eV}^2)\,. \tag{4}$$

From solar-neutrino deficit observations [7,8],

large-mixing-angle MSW [9] solution (LMA) (5)

$$\sin^2 2\theta_{\rm SOL} = 0.8\,, \quad \delta m^2_{\rm SOL} = 5, 15\times 10^{-5} ({\rm eV}^2)\,,$$

small-mixing-angle MSW [9] solution (SMA) (6)

$$\sin^2 2\theta_{\rm SOL} = 7\times 10^{-3}\,, \delta m^2_{\rm SOL} = 5\times 10^{-6} ({\rm eV}^2)\,,$$

vacuum oscillation solution [10] (VO)

$$\sin^2 2\theta_{\rm SOL} = 0.9\,, \delta m^2_{\rm SOL} = 7\times 10^{-11} ({\rm eV}^2)\,. \tag{7}$$

From the CHOOZ reactor experiments [11],

$$\sin^2 2\theta_{\rm CHOOZ} < 0.1 \text{ when } \delta m^2_{\rm CHOOZ} > 10^{-3} ({\rm eV}^2). \tag{8}$$

The four independent parameters of the MNS matrix are related to the above observables and CP phase :

$$2|U_{e3}|^2 = 1 - \sqrt{1-\sin^2 2\theta_{\rm CHOOZ}}\,, \tag{9}$$

$$2U^2_{\mu 3} = 1 - \sqrt{1-\sin^2 2\theta_{\rm ATM}}\,, \tag{10}$$

$$2U^2_{e2} = 1 - |U_{e3}|^2 - \sqrt{\left(1-|U_{e3}|^2\right)^2 - \sin^2 2\theta_{\rm SOL}}\,, \tag{11}$$

$$arg\,(U_{e3}) = -\delta_{\rm MNS}\,. \tag{12}$$

The first three equations are obtained for the observed mass-squared differences

$$\delta m^2_{\rm SOL} = \left|\delta m^2_{12}\right| \ll \left|\delta m^2_{13}\right| = \delta m^2_{\rm ATM}\,, \tag{13}$$

where $\delta m^2_{ij} \equiv m^2_j - m^2_i$.

3 Probability and mass hierarchies

The Hamiltonian in the matter is written as

$$\mathcal{H}_{\alpha\beta} = \frac{1}{2E_\nu}\left(\delta m^2_{13} U_{\alpha 3} U^*_{\beta 3} + \delta m^2_{12} U_{\alpha 2} U^*_{\beta 2} + A\delta_{\alpha e}\delta_{\beta e}\right)\,, \tag{14}$$

where α and β are flavor indices (e, μ, τ) and A measures the matter effect,

$$\begin{aligned} A &= 2\sqrt{2} G_F Y_e \rho E_\nu \\ &= 7.56\times 10^{-5}\left(\frac{\rho}{\rm g/cm^3}\right)\left(\frac{E_\nu}{\rm GeV}\right)\,. \end{aligned} \tag{15}$$

We assume that the matter density of the earth's crust is constant at $\rho = 3$. We can then diagonalize the Hamiltonian, eq.(14) as

$$\mathcal{H} = \frac{1}{2E_\nu}\tilde{U}\begin{pmatrix}\lambda_1 & 0 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_3\end{pmatrix}\tilde{U}^\dagger\,, \tag{16}$$

where $\tilde{U}$ is the MNS matrix in the matter. We introduce the oscillation phase parameters in the matter as

$$\tilde{\Delta}_{ij} = \frac{\lambda_j - \lambda_i}{\hbar c}\frac{L}{2E}\,. \tag{17}$$

By using eq.(16) and eq.(17), the oscillation probability in the matter is obtained as

$$\begin{aligned} P(\nu_\alpha\to\nu_\beta) = \delta_{\alpha\beta} - 4\Bigg\{ & {\rm Re}\left[\tilde{U}_{\alpha 1}\tilde{U}^*_{\beta 1}\tilde{U}_{\beta 2}\tilde{U}^*_{\alpha 2}\right]\sin^2\frac{\tilde{\Delta}_{12}}{2} \\ & + {\rm Re}\left[\tilde{U}_{\alpha 2}\tilde{U}^*_{\beta 2}\tilde{U}_{\beta 3}\tilde{U}^*_{\alpha 3}\right]\sin^2\frac{\tilde{\Delta}_{23}}{2} \\ & + {\rm Re}\left[\tilde{U}_{\alpha 3}\tilde{U}^*_{\beta 3}\tilde{U}_{\beta 1}\tilde{U}^*_{\alpha 1}\right]\sin^2\frac{\tilde{\Delta}_{31}}{2}\Bigg\} \\ & + 2\tilde{J}\left[\sin\tilde{\Delta}_{12} + \sin\tilde{\Delta}_{23} + \sin\tilde{\Delta}_{31}\right]\,, \end{aligned} \tag{18}$$

where

$$\tilde{J} = {\rm Im}\left[\tilde{U}_{\alpha 1}\tilde{U}^*_{\beta 1}\tilde{U}_{\beta 2}\tilde{U}^*_{\alpha 2}\right]\,, \tag{19}$$

for $(\alpha,\beta) = (e,\mu)\,, (\mu,\tau)\,,$ or (τ, e), the Jarlskog parameter [12] of the lepton sector in the matter.

There are four types of mass hierarchies, as shown at Table 1. When the MSW solutions are chosen for

Table 1: Four type mass hierarchies.

case	I	II	III	IV
δm^2_{12}	$\delta m^2_{\rm SOL}$	-$\delta m^2_{\rm SOL}$	$\delta m^2_{\rm SOL}$	-$\delta m^2_{\rm SOL}$
δm^2_{13}	$\delta m^2_{\rm ATM}$	$\delta m^2_{\rm ATM}$	-$\delta m^2_{\rm ATM}$	-$\delta m^2_{\rm ATM}$

the solar neutrino deficit problem, only the mass hierarchies I and III are relevant. Below we show results for

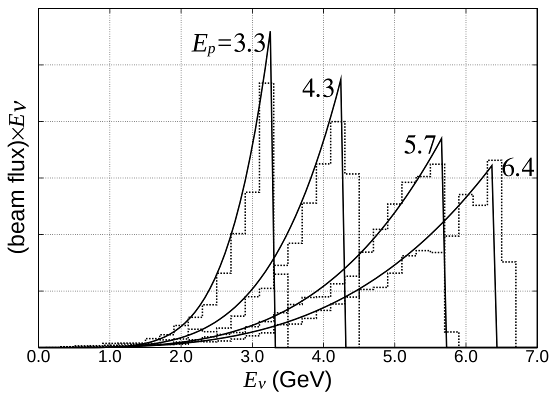

Figure 1: The Narrow Band Beam from HIPA. The horizontal axis is the neutrino energy (E_ν) and the vertical axis is the beam flux times E_ν.

all four mass hierarchies because the anti-neutrino oscillation probabilities in the matter are related to those for neutrinos,

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)_{\mathrm{I,II,III,IV}} = P(\nu_\alpha \to \nu_\beta)_{\mathrm{IV,III,II,I}}\,, \qquad (20)$$

in the limit of spherically symmetric earth. The number of anti-neutrino events for the mass hierarchy case I is obtained from that of neutrino events for the hierarchy IV, by taking account of the difference in flux and cross sections.

4 Beam and Detector

We examine pulsed-NBB, whose shape is shown in Figure 1. The horizontal axis gives the neutrino energy E_ν and the vertical axis gives the flux times E_ν. The histograms are obtained from the computer simulation and we use the smooth fitted curves parameterized by the neutrino peak energy, E_p, in the following analysis.

We examine the case of 100kt water-Cherenkov detector. The detector should distinguish the e-like, μ-like and neutral current events, but we do not use the neutrino-energy information from the detector in this analysis. That is, we assume the "counting experiment" in this analysis.

5 Results

The numbers of e-like and μ-like events are functions of only one variable, E_p, the peak energy of the NBB. The number of events, $N(e(\mu) : E_p)$ are obtained as

$$N(e(\mu) : E_p) = M N_A \int_0^{E_p} \sigma^{cc}_{e(\mu)}(E_\nu)\Phi(E_\nu, E_p) \times P_{\nu_\mu \to \nu_{e(\mu)}}(E_\nu) dE_\nu\,, \qquad (21)$$

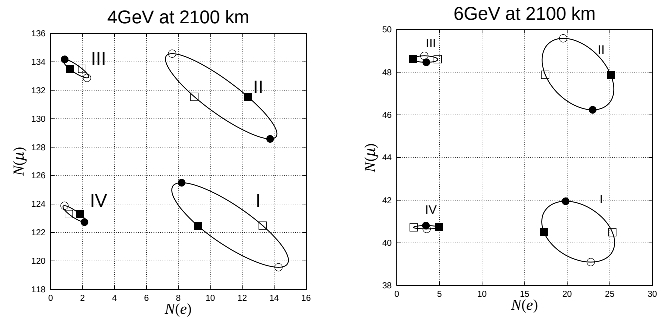

Figure 2: CP phase dependence of $N(e)$ and $N(\mu)$ at Beijing for the NBB with E_p = 4GeV (left) and E_p = 6GeV (right). $\delta_{\mathrm{MNS}} = 0°$ (solid-circle), 90° (square), 180° (open-circle), and 270° (open-square). The results are shown for $\sin^2 2\theta_{\mathrm{SOL}} = 0.8$, $\sin^2 2\theta_{\mathrm{CHOOZ}} = 0.1$, $\sin^2 2\theta_{\mathrm{ATM}} = 1.0$, $\delta m^2_{\mathrm{SOL}} = 1.0 \times 10^{-4}\mathrm{eV}^2$, and $\delta m^2_{\mathrm{ATM}} = 3.5 \times 10^{-3}\mathrm{eV}^2$.

where M is the detector mass, N_A is the Avogadro Number, $\sigma^{cc}_{e,\mu}(E_\nu)$ is the charged-current cross section for each species, $\Phi(E_\nu, E_p)$ is the NBB flux and $P_{\nu_\mu \to \nu_{e,\mu}}(E_\nu)$ is the transition or survival probability of ν_μ.

First, we show the CP phase dependence of the expected number of e-like and μ-like events at Beijing for the NBB with E_p =4GeV and 6GeV, and for 100ktyear. In this figure, we fix the mixing angles as $\sin^2 2\theta_{\mathrm{SOL}} = 0.8$, $\sin^2 2\theta_{\mathrm{CHOOZ}} = 0.1$, and $\sin^2 2\theta_{\mathrm{ATM}} = 1.0$, and the mass-squared differences as $\delta m^2_{\mathrm{SOL}} = 1.0 \times 10^{-4}(\mathrm{eV}^2)$ and $\delta m^2_{\mathrm{ATM}} = 3.5 \times 10^{-3}(\mathrm{eV}^2)$. In each figure, horizontal and vertical axis stand for the number of e-like and μ-like events, respectively. The solid-circle, square, open-circle, and open-square marks for $\delta_{\mathrm{MNS}} = 0°$, 90°, 180°, and 270°, respectively.

In Figure 3, we show the expected numbers of e-like and μ-like events per year at a 100kt detector on Beijing for the NBB with E_p = 4GeV (left) and 6GeV (right). Predictions of the VO scenario, the SMA solution, and the LMA solution with $\delta m^2_{\mathrm{SOL}} = 5 \times 10^{-5}$ and 15×10^{-5} eV^2 are shown. Five points or five circles with increasing $N(e)$ show expectations for five values of $\sin^2 2\theta_{\mathrm{CHOOZ}}$, 0.02, 0.04, 0.06, 0.08, to 0.1. The predictions of the VO scenario are common for the mass hierarchies I and II, which are shown by the five dots with larger $N(e)$, and also for the case III and IV, the five dots with smaller $N(e)$. The SMA scenario predicts smaller $N(\mu)$ in cases I and IV, and larger $N(\mu)$ in cases II and III than that of the VO scenario. The LMA scenario predicts even smaller $N(\mu)$ in cases I and IV, and larger $N(\mu)$ for cases II and III, where the deviation from the VO scenario is more significant for larger $\delta m^2_{\mathrm{SOL}}$.

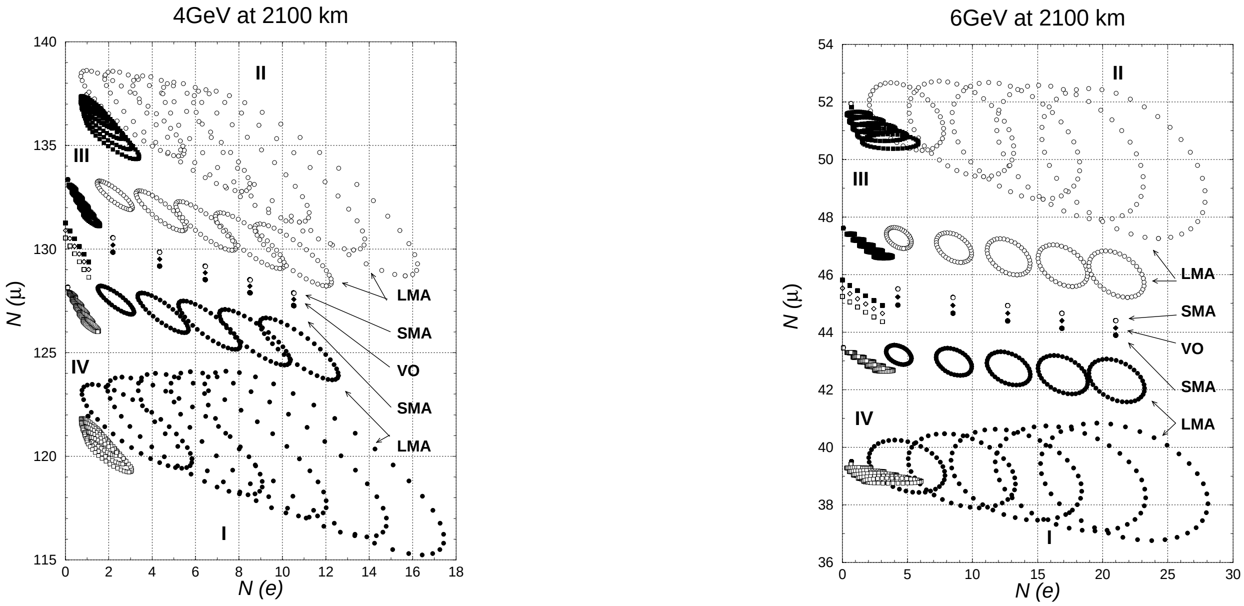

Figure 3: The neutrino parameter dependence of the expected event numbers for the NBB with E_p = 4GeV(left) and 6GeV(right) and for 100ktyear at Beijing.

6 Summary

In this paper, we study the prospects of very long base-line (VLBL) neutrino-oscillation experiments with the High Intensity Proton Accelerator (HIPA). We present results for a VLBL experiment between HIPA and Beijing, where the base-line length is about 2100 km. We propose to use conventional pulsed-narrow-band ν_μ beams and a huge water-Cherenkov detector of 100kt in mass. The detector should distinguish e-like, μ-like and neutral current events but it is not required to measure the neutrino-energy. We study the sensitivity of such an experiment to the signs and the magnitudes of the neutrino mass-squared differences, the mixing angles, and the CP phase of the 3×3 lepton flavor mixing matrix (MNS matrix), by using the $\nu_\mu \to \nu_e$ transition probability and the ν_μ survival probability. We find that the neutrino mass hierarchies can be determined from this experiment within several years. The CP phase can be measured if both the mass-squared difference and all the mixing angles of the MNS matrix are sufficiently large.

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